UK CLIMATE PROJECTIONS

Interpretation and use of future snow projections from the 11-member Met Office Regional Climate Model ensemble

UKCP09 technical note

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1 Summary

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1.1 Probabilistic projections of future changes in snow were not provided in UKCP09, due to the statistical methodology producing unrealistically large uncertainties when future changes approached a reduction of 100%.

1.2 However, daily values of snowfall rate are available at 25 km resolution from the ensemble of 11 Met Office regional climate model (RCM) variants run for UKCP09. This ensemble was run for the period 1950–2099, driven by the UKCP09 Medium scenario of future emissions of greenhouse gases and aerosols. There are no corresponding RCM projections for the High or Low emissions scenarios. Data are available from the Climate Impacts LINK website (see http://badc.nerc.ac.uk/data/link), and provide an important resource for users who require time series of snow events at 25 km spatial resolution for impact assessments and adaptation planning. This document assesses this information, focusing primarily on numbers of days with snow falling. Users should be clear that these data are not probabilistic in nature but provide a sample of 11 possible futures which do not encompass the full range of possible future changes in snow, and cannot be used to estimate the relative likelihood of different changes.

1.3 Days of falling snow in the RCM are defined as days when the snowfall rate exceeds 0.02 mm/day. The use of such a threshold is justified both by the desirability of removing insignificant snow events ('light flurries') that would not be measurable in practice, and also by differences between the spatial and temporal sampling of the simulated and observed snow diagnostics (See 1.4 below).

1.4 The simulated frequencies of days with snow falling in the RCMs show biases when compared to long-term climatological means derived directly from observations. The most notable regional biases in snow days are in the Scottish western Highlands where simulations of the baseline period have too many snow days by 40% to over 80% in winter, and positive biases on the west coast of northern England and Wales. This is possibly due to cold biases in these areas with respect to temperature observations.

1.5 There is an issue of representativeness of the observations in the assessment of the RCM biases. The fact that the observations are made at a single point and the up-scaling to the 25 km grid boxes of the RCM scale may not represent the RCM diagnostic of a fraction of the precipitation falling as snow for the whole 25 km grid box. Furthermore the observations are at a frequency of no greater than once per hour leading to the possibility of temporal sampling errors.

1.6 Projections of future change (2070–2099 minus 1961–1990) in days of falling snow show large fractional reductions that are largest in the south and least for western Scotland, with ensemble mean winter changes of 85% and 55% respectively for the chosen threshold of 0.02 mm/day. Repeating the calculation for an alternative threshold of 0.1 mm/day reduces the future changes by approximately 10%. This shows that the projected changes are only modestly sensitive to plausible variations in the choice of threshold. Changes in the 90th percentile of winter snowfall rate, a measure of heavy snow events, simulates reductions of greater than 80% for most of the UK. Reductions over Scotland are typically 60%. One ensemble member does not follow this pattern and predicts reductions for England and Scotland of generally 30% or more but increases for small regions including southern England of over 20%.

1.7 We also document projected changes in mean snowfall rate, comparing the spread in the ensemble of RCM projections for winter in the 2080s against the single ensemble-mean projection provided in the UKCP09 projections report (Murphy *et al*. 2009). While the individual ensemble members typically show significant spread around the ensemble mean, there is a robust indication of significant reductions, consistent with levels of warming (typically in the range 2 to 5°C) projected by the end of the century. The spread of RCM changes is generally similar to that found in the corresponding ensemble of global climate model (GCM) projections run for UKCP09, although there are some differences due to downscaling signals introduced by the improved resolution of regional physiographic influences (such as the effects of mountains and coastlines) in the RCMs. The results are also compared against projections from an international ensemble of alternative climate models. These also show substantial reductions in mean snowfall rate, in good qualitative agreement with the perturbed physics ensembles of RCM and GCM results. However, the spread of the multi-model projections is somewhat wider, demonstrating that the RCM ensemble expresses only a relatively limited range of possible changes consistent with current understanding and worldwide modelling capabilities.

1.8 In summary, the RCM ensemble provides a spread of plausible alternative projections of changes in characteristics of snowfall events for the UK. However, the presence of regional biases in the simulations of historical climate (here, 1961–1990) implies that users requiring information on absolute characteristics of future snow events, rather than simply a set of projected changes, will need to use a bias correction strategy to allow for the historical errors, although this will only be feasible where suitable observational data exists. For changes in mean snowfall rate, comparison against an independent ensemble of international global models supports the indication of substantial reductions found in the RCM ensemble, but also shows that the latter does not capture the full spread of possible modelling uncertainties. A similar comparison for projections of changes in snow days cannot be made, as daily snowfall data is not available from the multi-model ensemble. However, the spread of uncertainties in other snow-related variables in the RCMs is also likely to underestimate the full spread of possible outcomes, as for mean snowfall rate. Therefore, the RCM ensemble can be used to assess the expected nature of future changes, but not to quantify the likelihood of different levels of change. Nevertheless, users requiring further information beyond that provided in this document, such as changes in the depth of lying snow, should consider further analysis of the RCM data, whilst taking account of the limitations noted here (as documented in Section 3). We note that corresponding data may not be available from alternative ensembles of model projections, dependent on the metric of interest.

2 Introduction

2.1 As discussed in the UKCP09 climate projections science report (Murphy *et al*. 2009), it was not possible to provide probabilistic projections of future changes for certain variables (soil moisture, latent heat flux, snowfall rate and wind speed). The probabilistic projection methodology involves sampling climate modelling uncertainties by combining results from perturbed variants of the HadCM3 configuration of the Met Office global climate model with projections from alternative international climate models. In the case of snowfall, some climate models project small but non-zero values in the future, implying changes relative to the baseline climate that are close to the absolute lower bound of –100%. Under these conditions, statistical contributions to the uncertainties captured in the UKCP09 methodology were found to become unrealistically large, and hence probabilistic projections were not provided.* In their absence, there are four possible alternative sources of projections of transient changes during the 21st century:

- At the global climate model scale, a 17-member 'perturbed physics ensemble' (hereafter referred to as PPE_GCM) of HadCM3 variants sampling uncertainties in surface and atmospheric model parameters (see Section 3.2.4 of Murphy *et al*. 2009**), and driven by the SRES A1B emissions scenario, also identified as the UKCP09 Medium scenario. However, only monthly data are available. This means that the use of daily thresholds to eliminate unrealistic light snowfall events cannot be performed. However, diagnostics likely to be dominated by more significant snow events and which integrate over time, such as monthly mean snowfall rate or lying snow thickness, are not likely to be significantly affected by this issue.

- A multi-model ensemble (MME) of projections of 21st century climate from alternative global climate models (also using SRES A1B emissions) which contributed to the IPCC Fourth Assessment Report (see Meehl *et al*. 2007).*** Only monthly mean snow diagnostics are available and it is not known whether these models also exhibit the 'light flurry' issue of HadCM3.

* Further details can be found in Section 3.3 of Murphy *et al*. (2009).

** Noting that the PPE_GCM ensemble was referred to as PPE_A1B in Section 3.2.4 of Murphy *et al*. (2009).

*** Note that this multi-model ensemble of transient climate change projections is different from the multi-model ensemble of projections of equilibrium climate change (response to doubled CO_2) used in the construction of the UKCP09 probabilistic projections (for reasons described in Section 3.2.8 of Murphy *et al*. 2009).

- An 11-member ensemble of perturbed variants of the Met Office regional climate model (PPE_RCM), driven from 1950–2099 by global projections from 11 members of the PPE_GCM ensemble.

- A multi-model ensemble of regional climate model projections from the European Union ENSEMBLES project.

2.2 Data from the PPE_GCM and PPE_RCM ensembles is available from the Climate Impacts LINK project, operated by the British Atmospheric Data Centre (BADC); see http://badc.nerc.ac.uk/data/link, with access conditions described at http://badc.nerc.ac.uk/conditions/ukmo_agreement.html. Data from the global multi-model ensemble can be accessed from the Program for Climate Model Diagnosis and Intercomparison (PCMDI), based in California, which has collected model output from simulations contributed by modelling centres around the world, as part of the Coupled Model Intercomparison Project (CMIP3) of the World Climate Research Programme. The CMIP3 multi-model dataset can be freely accessed for non-commercial purposes via http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php.

2.3 As noted above, the RCM projections from the ENSEMBLES project (available from http://ensemblesrt3.dmi.dk/) provide a potential additional source of fine scale projections of snow. These projections use the same emissions scenario as PPE_RCM (the UKCP09 Medium scenario), and consists of a partly-filled matrix of simulations in which a number of global models developed in Europe are used to drive a number of European regional models. Data are freely available, subject to conditions at http://ensembles-eu.metoffice.com/docs/Ensembles_Data_Policy_261108.pdf. The regional models in these experiments are configured at either 25 or 50 km horizontal resolution, the simulations running from 1951 to either 2050 or (in some cases) 2100. We do not evaluate the ENSEMBLES projections in this report (although we note that three of the global model projections providing driving data are taken from the PPE_GCM ensemble run for UKCP09, and one of the regional models is taken from the PPE_RCM ensemble). Users wishing to assess these projections will need to perform their own evaluation, for example along similar lines to the evaluation of PPE_RCM projections provided below.

2.4 The 11 member PPE_RCM ensemble provides an opportunity to access snow projections expressed at a finer spatial scale (25 km resolution) compared to the global model projections discussed above and at higher temporal (daily) resolution, and is therefore potentially a more attractive option for use in impact and adaptation studies for the UK. Here we assess the strengths and limitations of the data from this ensemble.

2.5 Each of the 11 RCM variants in the PPE_RCM ensemble run for UKCP09 was configured from the corresponding variant of the PPE_GCM ensemble, using the same representations of atmospheric dynamical and physical processes, including perturbations to model parameters matching those implemented in the relevant driving global projection. The RCM projections were run at 25 km horizontal resolution, using the European domain shown in Figure 3.8 of Murphy *et al.* (2009), driven at the lateral boundaries by time series of variables (such as temperature and winds) saved from the corresponding global projection. Sea surface temperatures and sea-ice extents were also prescribed using values saved from the relevant global projection, since the regional model used in UKCP09 (like most RCMs) does not include an interactive ocean component. The purpose of RCMs is to provide high resolution climate projections consistent with their driving global model projection at spatial scales skilfully resolved by the latter, but adding realistic detail at finer scales. This is commonly referred to as downscaling. Further details of the RCM projections can be found in section 3.2.11 of Murphy *et al*. (2009). The potential advantages of projections from RCMs over those from global models are that they can capture detailed spatial contrasts not resolved in the global models, particularly those arising from mountains and coastlines, and that they can capture climate variability and extreme events more faithfully, particularly aspects arising from regional-scale processes. Their main limitation is that they inherit larger scale biases from their driving global simulations, so cannot correct these. See also Chapter 5 of the UKCP09 Climate Change Projections Report (Murphy *et al*. 2009).

3. Evaluation of RCM snowfall days in present-day climate

3.1. A validation of RCM days with snow falling was performed using observations at meteorological observing stations from 1961–1990. The number of available stations varied from near 100 at the beginning of the period to 400–500 by the end. These were initially interpolated to a 1 km resolution grid of the UK and then aggregated to the 25 km grid of the RCMs to provide 30 year averages of days with snow falling for each season. Results for winter (December, January, February – DJF) are shown in Figures 1a and b as an example of the two grids.

3.2. The 1 km interpolation used values from neighbouring points and a correction for height (Perry and Hollis, 2005). Figure 2 shows the observed average number of snowfall days for each season on the 25 km grid, defining spring as (March, April, May – MAM), summer (June, July, August – JJA), and autumn (September, October, November – SON). We note that the observed data are representative of snow events observed at point locations, and are based on observations taken in a variety of sampling regimes. The spatial and temporal sampling employed in the observed dataset is therefore different from the RCM results, which represent accumulated daily snow amounts aggregated over a spatial region of 25 x 25 km^2.

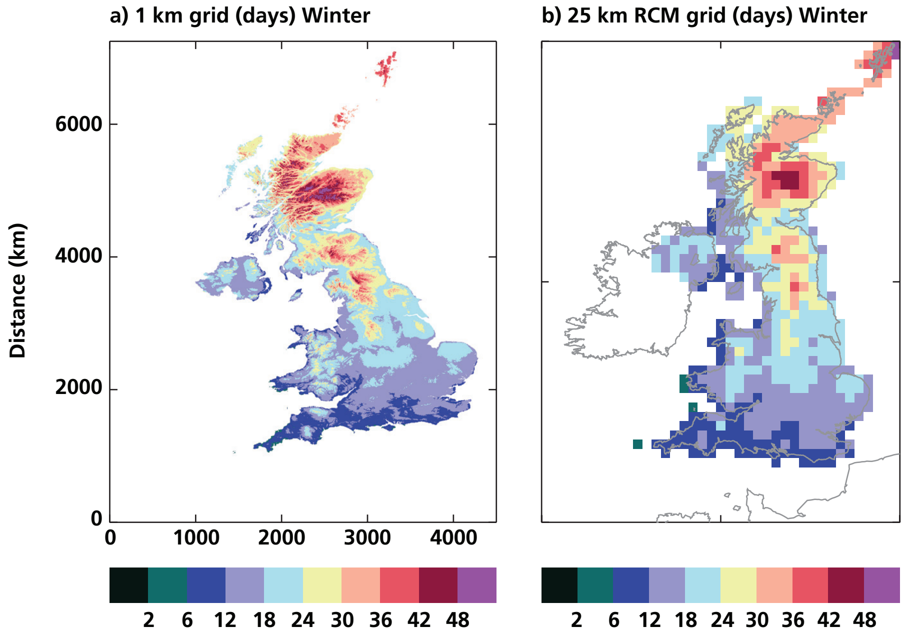

Figure 1: Gridded observations of days with snow falling averaged over 1961–1990 for December to February (DJF) at a) 1 km resolution b) 25 km resolution, corresponding to regional climate model (RCM) grid boxes.

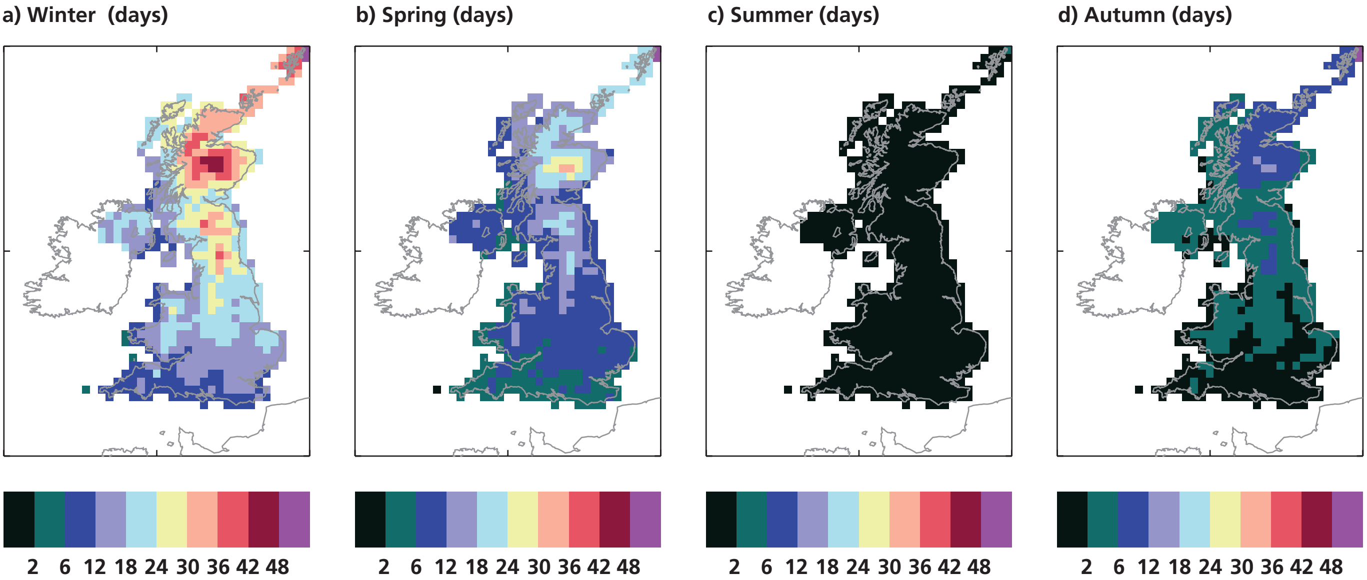

Figure 2: Observed number of days with snow falling on the 25 km RCM grid, averaged over 1961–1990 for a) DJF b) March–May (MAM) c) June–August (JJA) d) September–November (SON).

3.3. Model snowfall rate was used to define days with snow falling from which 30 year average seasonal climatologies were calculated from the period 1961–1990 for each RCM ensemble member. It is necessary to use a threshold for snowfall rate to define a 'snow days' as the model frequently produces very small amounts of snow ('light flurries') which are far smaller than any measurable rate, often at the numerical precision level of the computed diagnostic. This is a known feature of the Met Office Unified Model code, which has been noted when configured for weather prediction (Martin Willett, personal communication, August 2010) as well as the climate simulations assessed here.

3.4. The use of such a threshold is justified both to avoid counting tiny, physically insignificant snow events as explained in Section 3.2, and also to account for the different spatial and temporal sampling of events between the simulated and observed datasets (Section 3.1). However, the choice of this threshold does have a direct impact on the simulated number of days of snow (higher choices reduce the number of diagnosed events from the model runs), and hence on the validation against observations. In practice, we tried several alternative thresholds in the range 0.01–0.1 mm/day, and selected 0.02 mm/day, on the basis that this choice essentially ensures the least biased simulation of snow days, when averaged over spatial locations, seasons and ensemble members. Figure 3 shows seasonal percentage bias using this threshold in the 1961–1990 climatology for each member and ensemble mean. Summer is not considered further due to it having a small or zero number of snow days for most of the UK. While our choice of threshold succeeds (essentially by definition) in ensuring the least biased ensemble mean for the majority of the UK, biases are present in the values simulated for specific locations, seasons and ensemble members. In general there is a tendency for the RCM to produce too many snow days on the west coast and too few on the east whilst the ensemble spread spans zero for central England. The Scottish western Highlands always have too many snow days by 40% to over 80% in winter, spring and autumn. Positive biases also occur on the west coast of northern England and Wales. This is possibly due to the RCM exhibiting cold biases in these areas with respect to temperature observations (not shown).

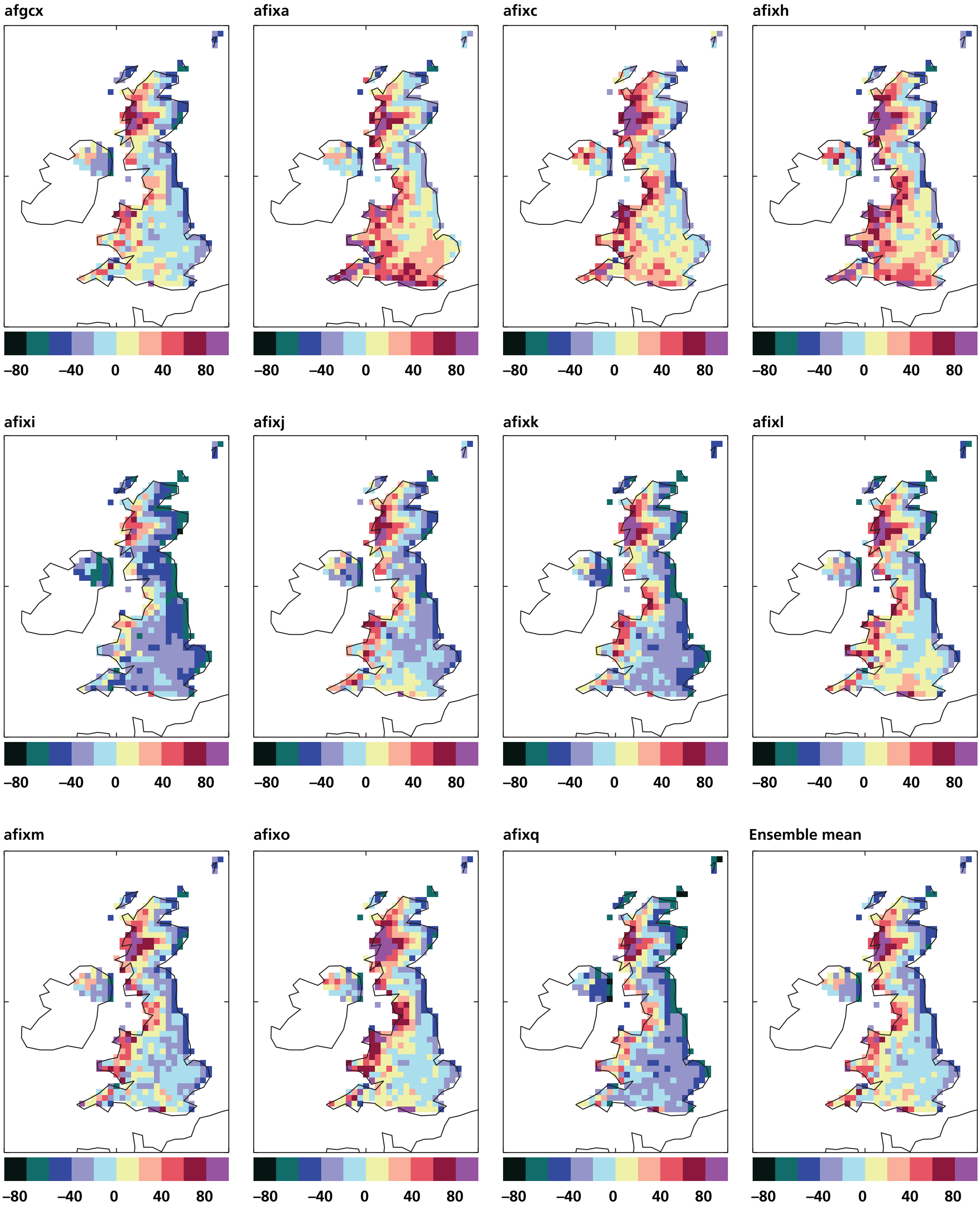

Figure 3: RCM member and ensemble mean seasonal biases in number of days with snow falling at a rate greater than 0.02 mm/day, expressed as a percentage of observations for winter, values calculated for 1961–1990. Points with fewer than 4 observed days with snow per year are masked out.

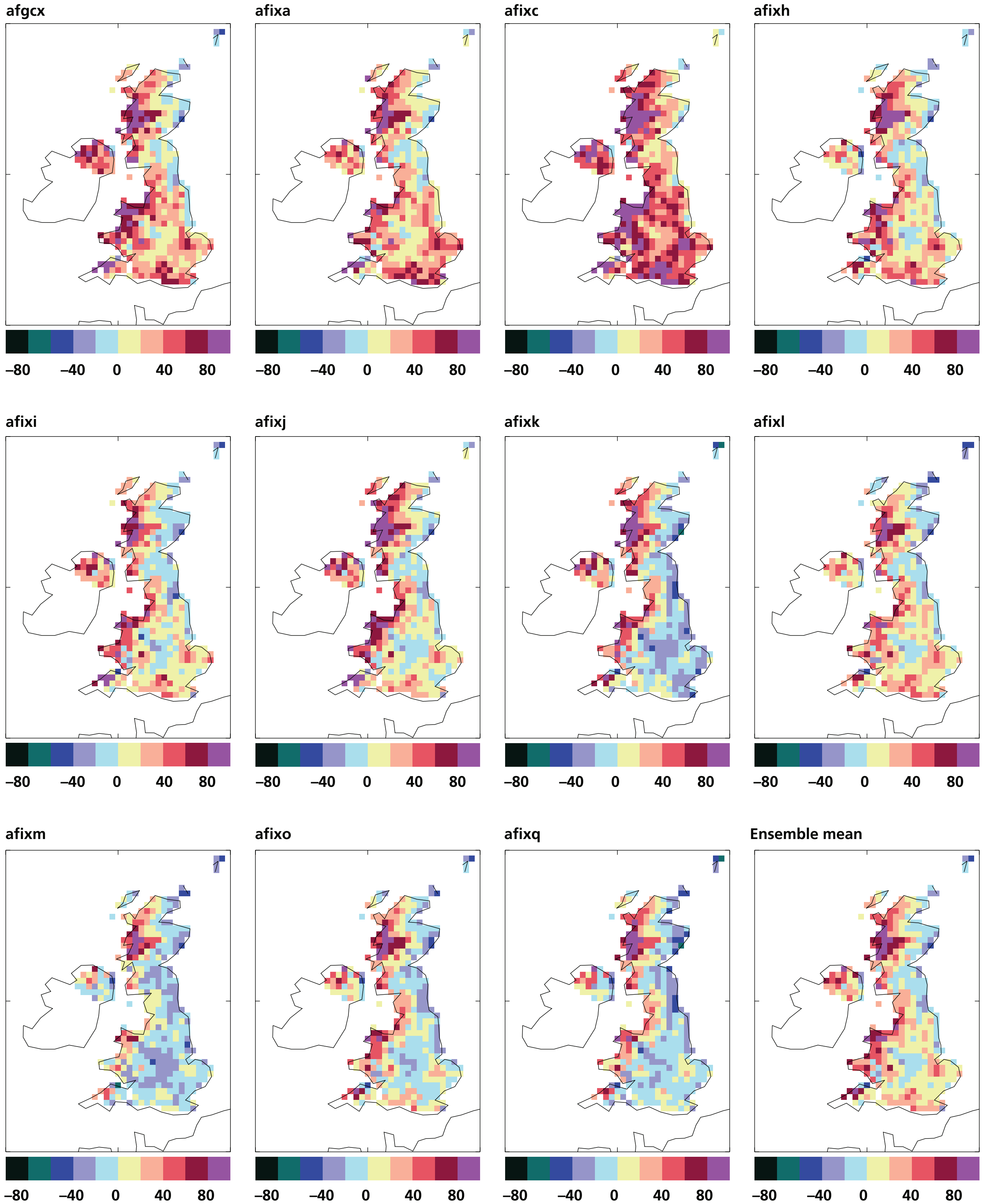

Figure 3 (continued): RCM member and ensemble mean seasonal biases in number of days with snow falling at a rate greater than 0.02 mm/day, expressed as a percentage of observations for spring, values calculated for 1961–1990. Points with fewer than 4 observed days with snow per year are masked out.

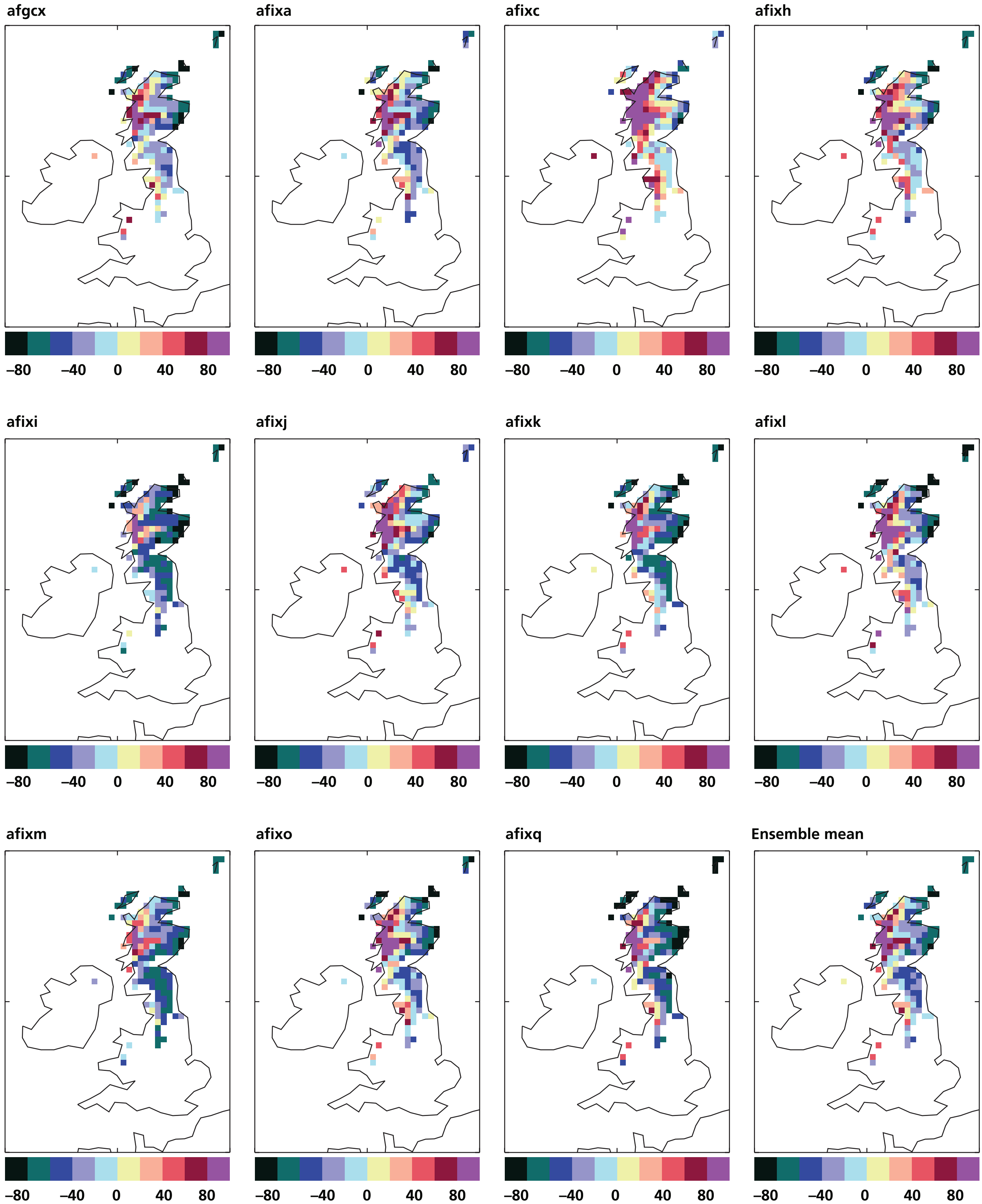

Figure 3 (continued): RCM member and ensemble mean seasonal biases in number of days with snow falling at a rate greater than 0.02 mm/day, expressed as a percentage of observations for autmun, values calculated for 1961–1990. Points with fewer than 4 observed days with snow per year are masked out.

3.5. This raises the question of whether model biases in the historical simulation of snow days affect the credibility of projected future changes. In general, regional changes in climate in response to anthropogenic forcing can arise from a complex combination of many potential remote and local influences. The relative influences of processes that drive the changes may not necessarily be the same as those responsible for present day climate. While the evaluation of past performance in simulating snow is an important check, it should not be assumed either that a reasonable historical simulation guarantees a credible projection of future changes, or that the presence of biases in the historical simulations (provided they are not too large) precludes the possibility of obtaining credible future projections. However, the presence of historical simulation biases does imply, in principle, the need to apply a postprocessing strategy to remove their effects, if users require to convert model projections of future change in some metric of interest (e.g. number of snowfall days, mean snowfall, intensity of extreme events, days or depth of lying snow, etc.) into plausible estimates of absolute future climate values. However, the feasibility of applying bias-correction techniques depends on the availability of suitable observational data.

3.6. Diagnostics of snowfall rate and depth of lying snow are available from the RCM ensemble, however, there are no corresponding gridded observations available for validation of the model simulations. However, results for future changes in mean snowfall rate have been included in the following section.

4. Assessment of projected future changes

4.1. The projected changes in the number of days with snow for the RCM ensemble are shown in Figure 4 for winter, spring and autumn using a threshold of 0.02 mm/day to define days with snow. There are very few grid points with days of snow for summer in the future so changes for this season are not shown. The ensemble-mean projected changes for winter (Figure 4a) show significant reductions in all regions. This is also the case for projected changes in mean snowfall rate, shown in Figure 4.33 of the UKCP09 projections report (Murphy *et al*. 2009). The individual ensemble members in Figure 4a show variations in the magnitude of the projected change, but confirm the robustness of the sign of the change. The projections are consistent with the expected influence of warming temperatures. By the 2080s, the ensemble members project levels of warming in winter ranging from 2 to 5°C, which significantly reduces the occurrence of sub-zero near-surface temperatures . Significant reductions in the number of days with snow are also seen in other seasons, for all regions. The largest fractional reductions occur in spring and autumn, typically >70%, with values of 40–70% occurring in winter. Reductions are smallest for the highlands of Scotland (c. 70, 50 ,40% for autumn, spring and winter respectively) but with a some spatial variability, and are relatively constant but larger across the rest of the UK (c. 80, 70, 70% for autumn, spring and winter respectively) with some north–south gradient for spring with the largest reductions in the south. A number of ensemble members show increased reductions at the coast for winter. If we repeat the calculation using a larger threshold of 1.0 mm/day for snow events (not shown), there is little alteration to the patterns of change, but the magnitude of the projected reductions become approximately 10% larger. This shows that while the magnitudes of historical simulation biases are quite sensitive to the choice of threshold, the sensitivity of the projected changes is relatively modest.

4.2. Changes in the 90th percentile* of snow fall rate, a measure of 'heavy' snow events, are shown in Figure 5 for winter, spring and autumn. The general pattern of large reductions (40–100%) is maintained but the intra-ensemble spread and spatial variation across the UK for individual members are much larger. This is not surprising, and probably reflects the substantial sampling uncertainties associated with projections of relatively rare events. For this reason, the large levels of spatial heterogeneity seen at small scales in the response patterns (sometimes including isolated points of increase immediately adjacent to projected reductions) are unlikely to be robust and

* Calculated through linearly interpolating between ranked values with respect to probability.

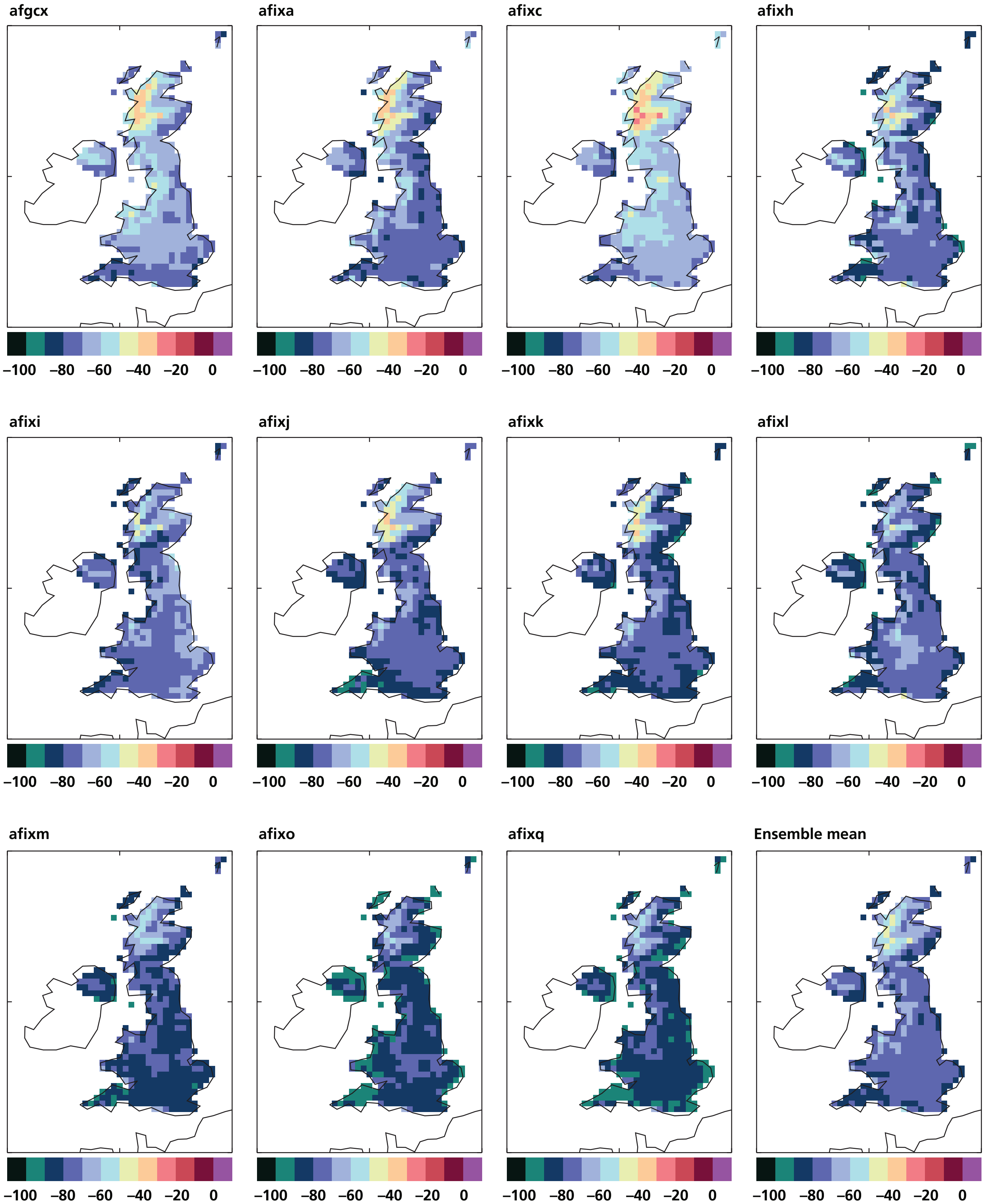

Figure 4: Changes in number of days with snow falling (%) in winter for 2070–2099 relative to 1961–1990, for the 11 individual RCM projections and ensemble-mean. Points with fewer than 4 observed days with snow per year are masked out.

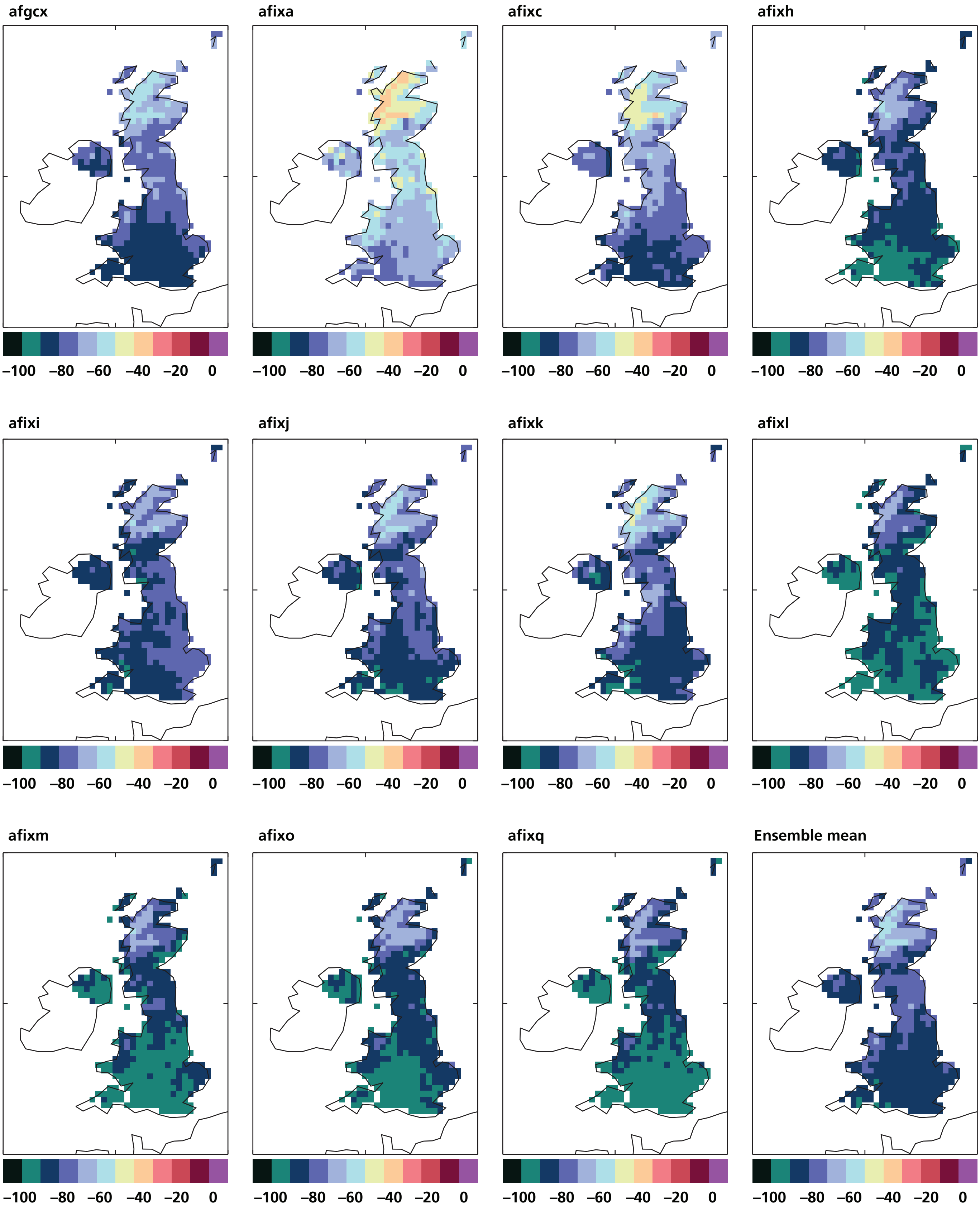

Figure 4 (continued): Changes in number of days with snow falling (%) in spring for 2070–2099 relative to 1961–1990, for the 11 individual RCM projections and ensemble-mean. Points with fewer than 4 observed days with snow per year are masked out.

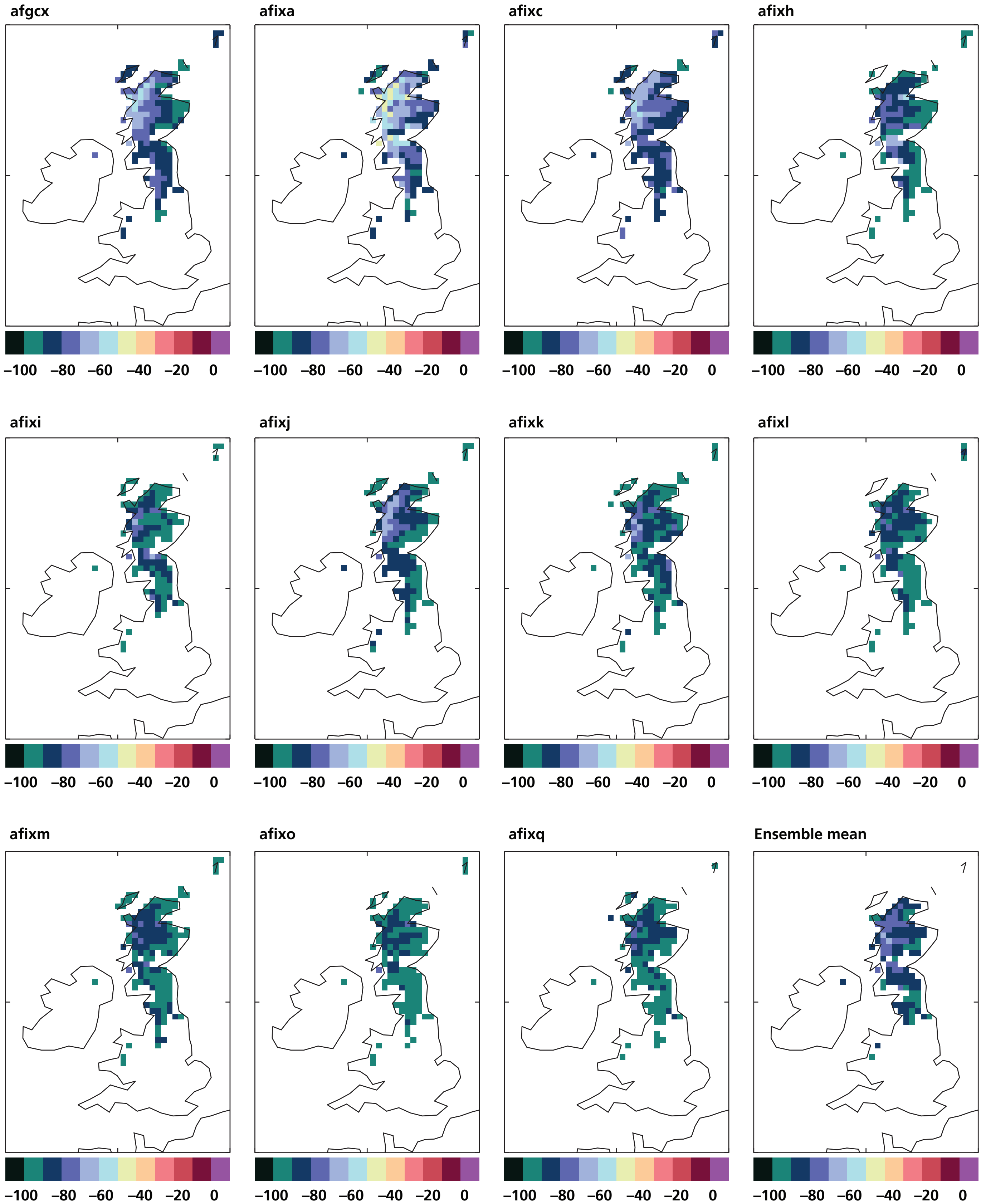

Figure 4 (continued): Changes in number of days with snow falling (%) in autumn for 2070–2099 relative to 1961–1990, for the 11 individual RCM projections and ensemble-mean. Points with fewer than 4 observed days with snow per year are masked out.

should not be taken as specific predictions for a small region. Rather, the focus should be on the guidance on future changes in heavy snow events provided by the ensemble for larger regions (e.g. at the country wide scale). As such these would suggest that for all of the UK winter and autumn the intensity of such events will reduce by greater than 80% whilst for spring the reductions are greater than 40%. In winter, one ensemble member ('afixc') does show smaller reductions than the other ten members, and projects increases in heavy events over some parts of Wales and southern England. The warming for this member is typical of the ensemble so these increases are not due to limited warming. These results suggest that although in general there is a reduced likelihood of snowfall and of reduced snowfall rate, large snowfall events in the future cannot be excluded. A more detailed study would be required to determine the relative likelihood of the most severe snowfall events compared to the present.

4.3. For the metrics considered above, it is not possible to compare the responses of the RCM ensemble against projections from alternative ensembles of projections listed in Section 2.1 However, such a comparison can be made for changes in the time-averaged snowfall rate, as this diagnostic was saved for the 17-member PPE_GCM ensemble of HadCM3 variants (11 of which were used to drive the RCM ensemble), and also for a multi-model ensemble of 15 of 21st century projections run for the IPCC Fourth Assessment report. Figure 6 shows a comparison of winter changes in seasonal mean snowfall rate for six regions covering the UK and Ireland (corresponding to land points in the HadCM3 GCM), alongside corresponding changes for the average of all RCM points within each GCM grid box. All three datasets show substantial ensemble-mean (red points) reductions in mean snowfall. This occurs despite the occurrence (typically) of increases in total precipitation, confirming that the reductions in snow occur due to a substantial shift from snow to rain events associated with projected increases in temperature. All three ensembles show a substantial spread of responses about the ensemble-mean. The MME always shows the largest spread. This confirms the general advice given in the UKCP09 projections report that the PPE_RCM ensemble, while providing a significant spread of plausible projections, does not (and was not designed to) capture the full range of modelling uncertainties, and therefore cannot be used in isolation to estimate likelihoods of different levels of change. Interestingly, the PPE_RCM ensemble projects slightly larger ensemble-mean reductions than either of the global model ensembles, for all regions of Figure 6. This is greatest over Ireland, and may arise from the improved resolution of regional land/sea contrasts and mountains in the RCM simulations, however, further investigation of the impact of downscaling in these results is beyond the scope of this report. Similar comparisons cannot be carried out for changes in snow days or heavy events, due to the unavailability of archived daily data from the GCM ensembles. However, we find that changes in mean snowfall rate are generally quite strongly correlated with changes to snow days and heavy snowfall events in the RCM projections, so it is likely that the RCMs will not capture the full range of plausible changes in those variables either.

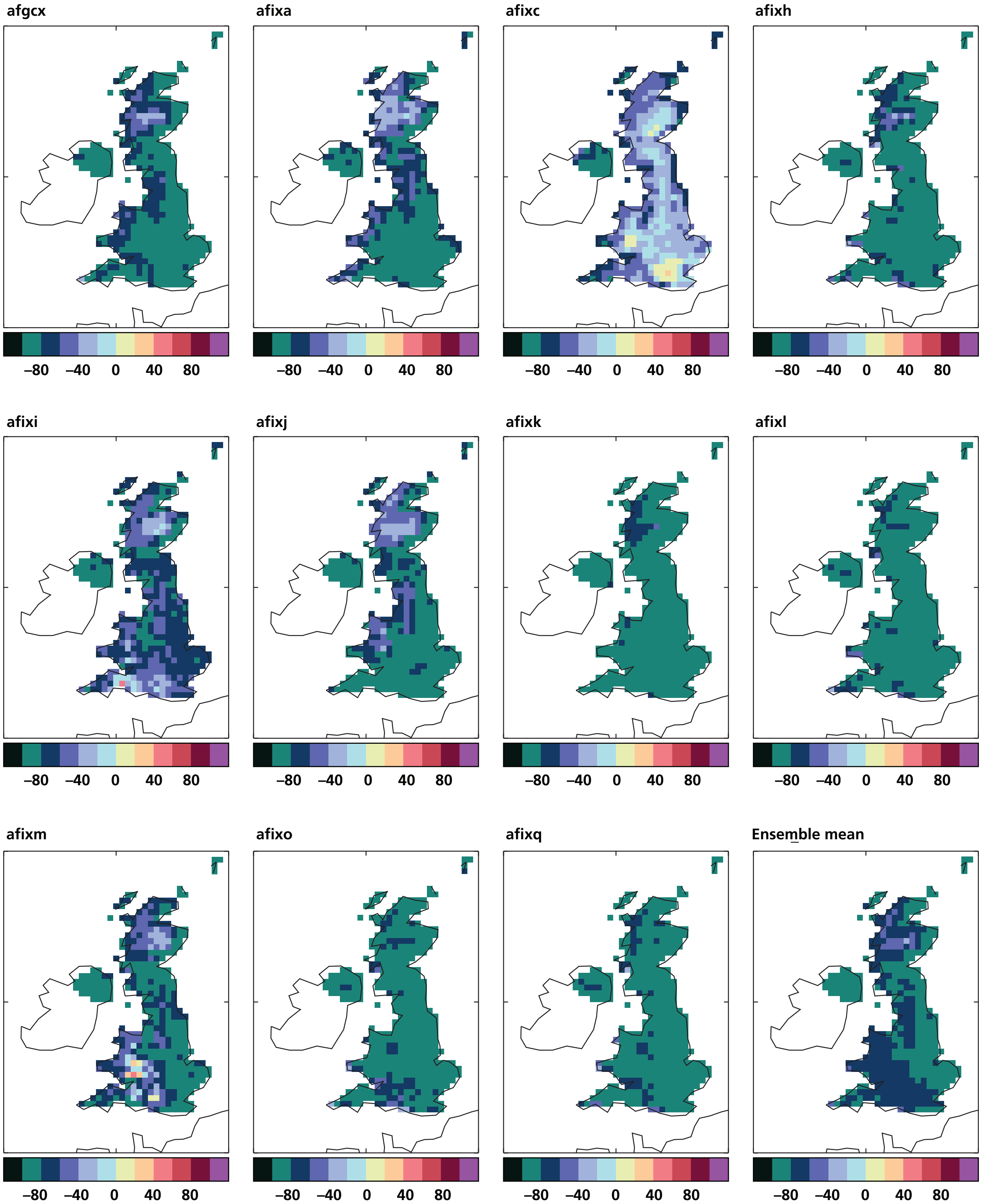

Figure 5: Percentage changes in the 90th percentile of snow fall rate for winter for 2070–2099 relative to 1961–1990, for the 11 individual RCM projections and ensemble-mean. Points with fewer than 4 observed days with snow per year are masked out.

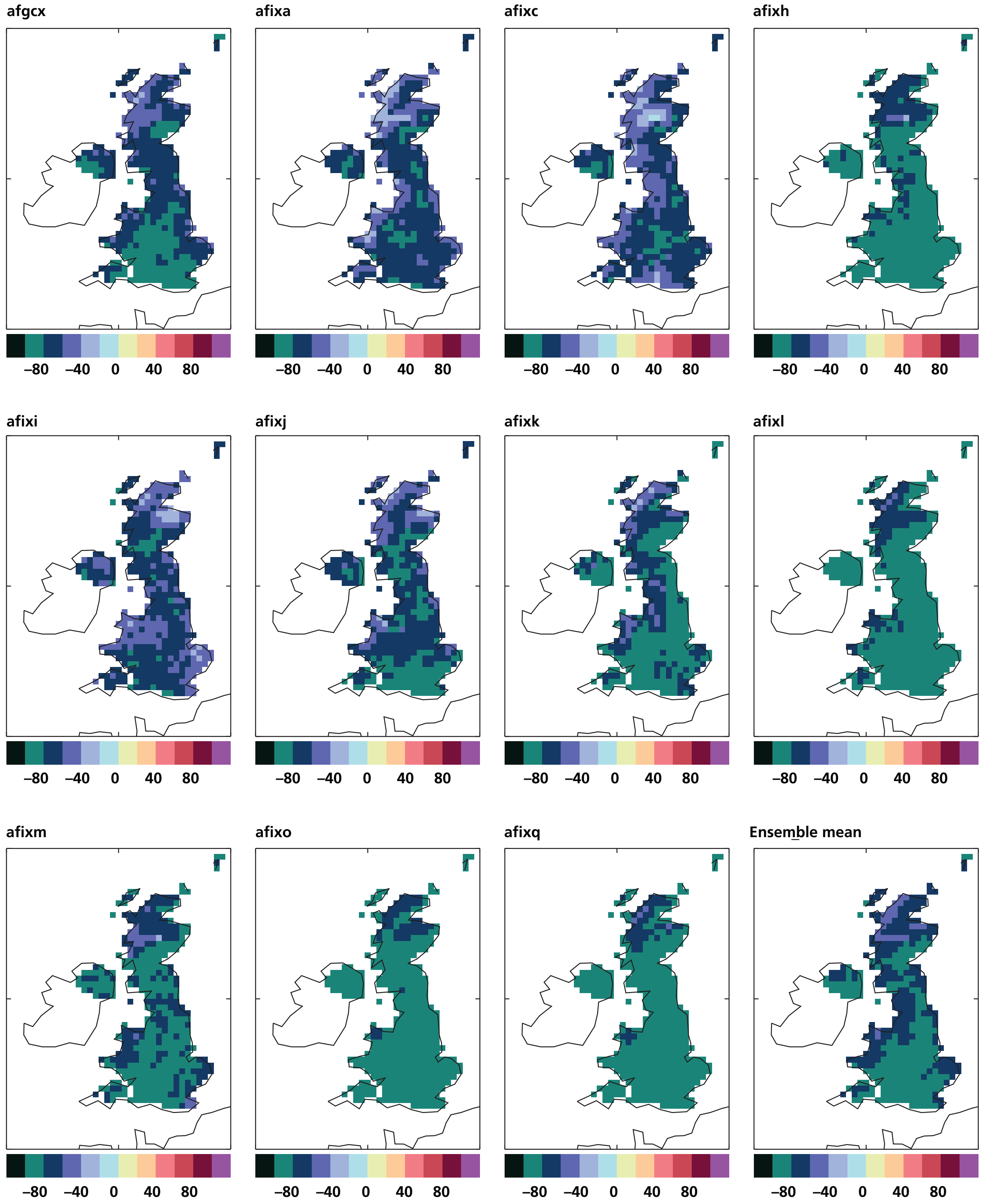

Figure 5 (continued): Percentage changes in the 90th percentile of snow fall rate for spring for 2070–2099 relative to 1961–1990, for the 11 individual RCM projections and ensemble-mean. Points with fewer than 4 observed days with snow per year are masked out.

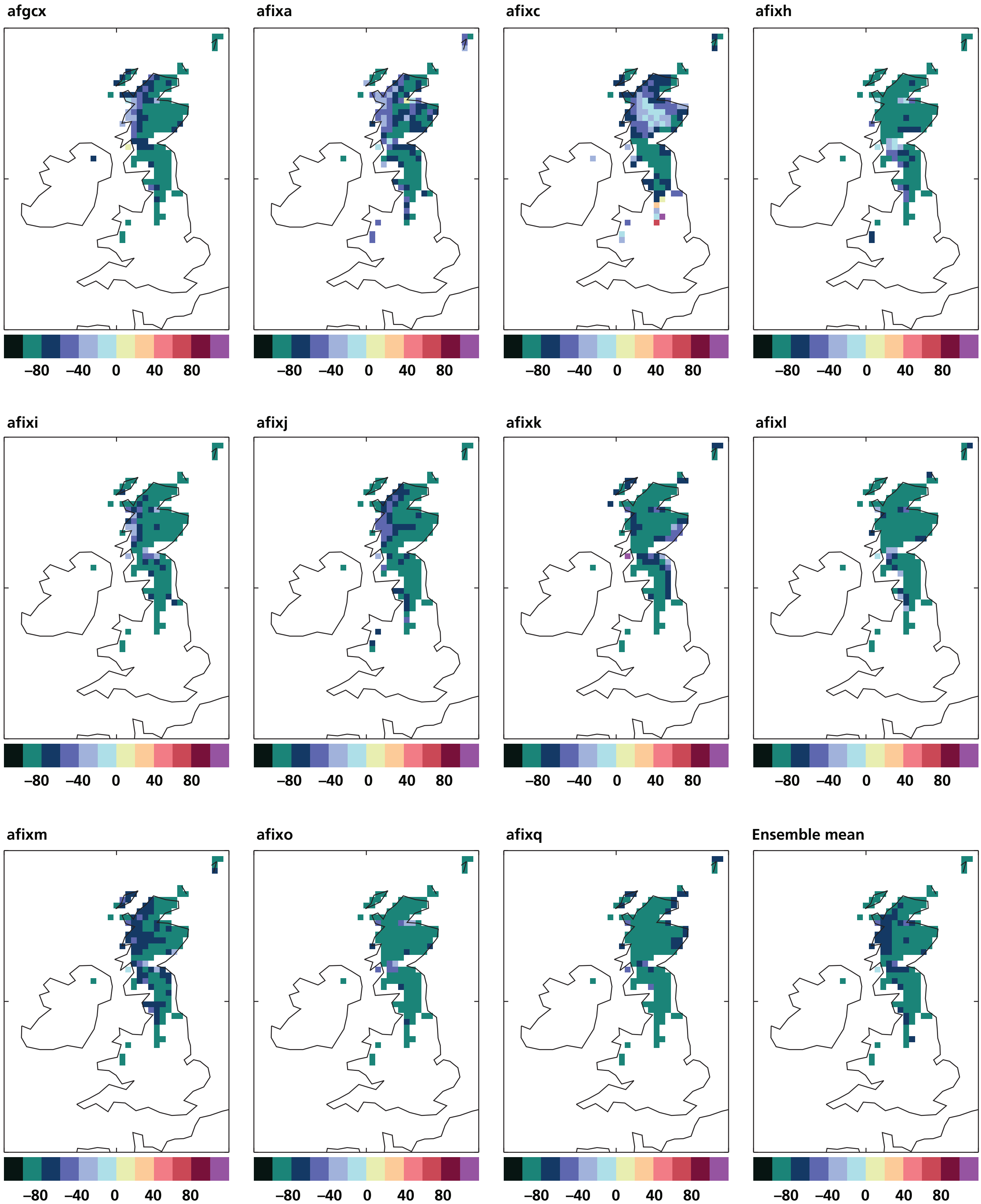

Figure 5 (continued): Percentage changes in the 90th percentile of snow fall rate for autumn for 2070–2099 relative to 1961–1990, for the 11 individual RCM projections and ensemble-mean. Points with fewer than 4 observed days with snow per year are masked out.

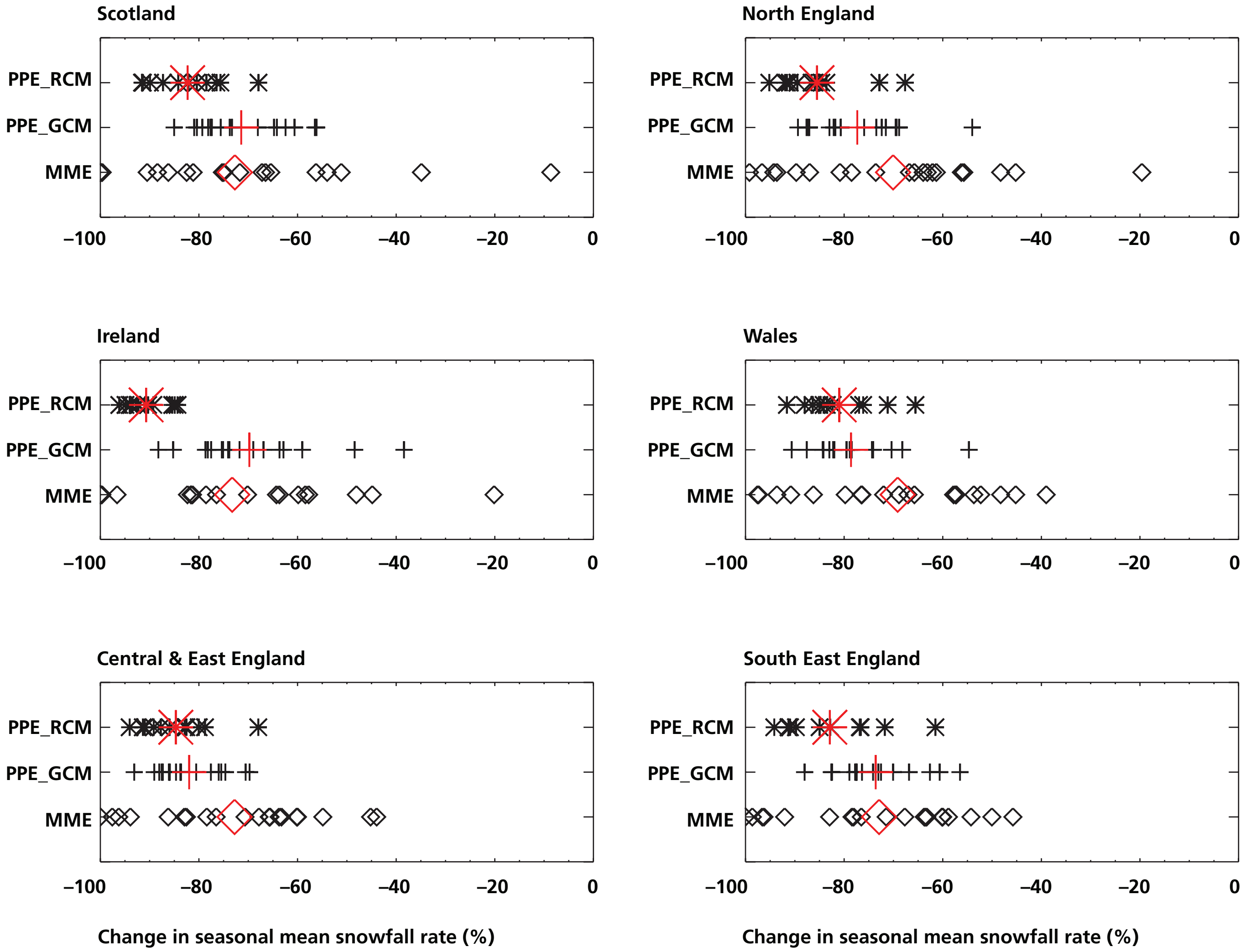

Figure 6: Percentage change in seasonal mean snowfall rate for DJF, 2070–2099 relative to 1961–1990, for the 6 land points representing UK and Ireland in HadCM3 and the PPE_RCM, PPE_GCM and MME ensembles. Members in black and ensemble-mean in red, RCM values are means of all gridpoints within the corresponding HadCM3 GCM gridpoint, MME values are nearest corresponding GCM grid point .

5. Conclusions

5.1. In summary, the RCM projections provide a useful dataset for the analysis of possible changes to future changes in snow. They simulate historical frequencies of snow days with some skill, but regional and seasonally varying biases are also present.

5.2. Significant future reductions in numbers of snow days, mean snowfall rates and the intensity of heavy events are projected for the end of the 21st century, consistent with the projections of warming temperatures. The sign of the changes is robust in most cases to the subset of modelling uncertainties sampled by the ensemble members. For changes in mean snowfall rate, the ensemble-mean changes are broadly consistent with those obtained from alternative ensembles of projections from global climate models, although this cannot be checked for the other metrics considered in this report due to a lack of daily data from the global model data archives.

5.3. The RCM ensemble possesses the advantage of accounting for high resolution regional influences of mountains, coastlines and land sea contrasts, however (as for other variables) it does not sample the full spread of possible outcomes consistent with present knowledge or modelling capability. The RCM ensemble should therefore be interpreted as providing a set of plausible alternative outcomes, but not as being suitable to attach likelihoods to different levels of change. Users requiring more detailed snow information than provided in this document should consider further analysis of the RCM data, whilst bearing in mind the limitations noted in this report.

Acknowledgements

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References

Meehl, G. A., *et al*. 2007. Global Climate Projections. In: Climate change 2007: The Physical Science Basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M. & Miller, H. L. (Eds.) Cambridge University Press, Cambridge, UK and New York, NY, USA.

Murphy, J. M., Sexton, D. M. H., Jenkins, G. J., Boorman, P. M., Booth, B. B. B., Brown, C. C., Clark, R. T., Collins, M., Harris, G. R., Kendon, E. J., Betts, R. A., Brown, S. J., Howard, T., Humphrey, K. A., McCarthy, M. P., McDonald, R. E., Stephens, A., Wallace, C., Warren, R., Wilby, R. & Wood, R. A. 2009. UK Climate Projections Science Report: Climate change projections, Met Office Hadley Centre, Exeter. (http://ukclimateprojections.defra.gov.uk/content/view/857/500/)

Perry, M. & Hollis, D. 2005. The development of a new set of long-term climate averages for the United Kingdom *Journal of Climatology* **25**, 1023–1039.